

## VIII. TRAVELING-WAVE TUBES

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### A. THREE-CM MEDIUM-VOLTAGE TRAVELING-WAVE TUBES

Several more tubes of the type described in the last progress report have been made; they have been modified by replacing the old gun by a new one. Their characteristics are substantially similar to those described previously. Present efforts are concerned with getting a good focusing magnet design.

### B. VELOCITY-MODULATED-INPUT TRAVELING-WAVE TUBE

The mechanical construction of the tube was revised by making the cavity of copper-plated, mild steel and sealing the helix-supporting glass tube to a Kovar ferrule instead of to molybdenum. These changes were made because of the technical difficulties of making the tube of non-magnetic materials, and the urgency of getting a thesis done. The rationalization for the changes was based on the fact that the steel cavity would shield the gun from the magnetic field, and that the beam would enter the magnetic field somewhere within the Kovar ferrule which would be just at the start of the helix.

Two tubes were assembled in this way, of which one broke while being tested. The other had the following characteristics:

Cavity loaded Q (matched input)	1000
Resonant wavelength	3.215 cm
Synchronous voltage	1350
Helix length	4 inches
1st anode current	2.8 ma
Helix current	2.4 ma
Collector current	.03 ma

Gain vs. input power is plotted in Figure VIII-1, for the conditions given. The small collector current is attributed to the fact that the helix support cracked during assembly and it was repaired so that the alignment between the helix and beam axes was uncertain. By running the anode (cavity) at 1600 volts, and the helix at 1350 the helix plus collector current was increased to 3.5 ma and the gain was increased by about 2 db.

Noise measurements were made, and a N.F. = 48 db was obtained. This is far in excess of any theoretical prediction, and is attributed to the

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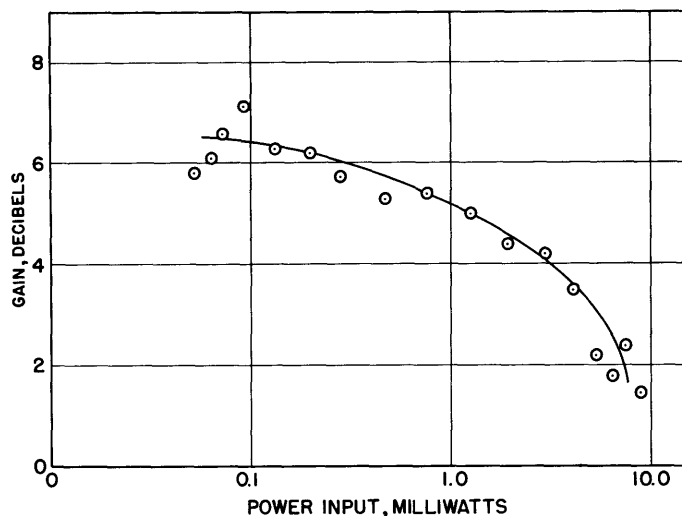


Fig. VIII-1 Velocity-modulated traveling-wave tube; gain vs. input power.

partition noise due to current interception in the cavity and along the helix.

The tube was used as an oscillator by connecting the output- to the input-waveguide through a phase shifter. Electronic tuning of about 12 Mc/sec between half-power points was obtained by varying beam voltage. This corresponded closely to the cavity bandwidth. The power output was about 7 Mw.

## C. THEORY

In the Progress Report of July 15, 1949 theoretical expressions for gain and noise figure were given. The gain expression is believed to be correct, but the noise figure expression is wrong, because the effect of the cavity was ignored. If the noise voltage induced in the cavity by the beam, and the resulting velocity and current modulations are computed, the resulting expression is

$$F = 2 + \frac{\gamma^2 e I_o Z_1 D^2}{kTA^2}$$

where

$$A = \left| e^{-j\frac{5\pi}{6}} - \beta C d + jC \right|, \quad D = \left| e^{-j\frac{5\pi}{6}} + jC - \beta C d - 2jC \frac{V_o}{I_o Z_1} \right|$$

$Z_1$  = cavity shunt impedance and  $d$  = distance from cavity gap to start of helix. Comparing with Pierce's expression for a conventional traveling-wave tube, we get

$$\frac{F_{v.m.}}{F_{Pierce}} = \frac{Z_1 I_o}{4C V_o} = \frac{Z_1}{4C Z_o}$$

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This indicates a disadvantage of about 10 db for the velocity modulated tube for common values of  $Z_1$ ,  $C$ , and  $Z_0$ . At very large currents it might be possible to make  $CZ_0 > Z_1$ , but this seems to be of little use.

This work is described in detail in a master's thesis, M.I.T. Department of Electrical Engineering, 1949, by Philip M. Lally.

P. M. Lally

### D. LOW-VOLTAGE THREE-CM TRAVELING-WAVE AMPLIFIER

#### 1. Helix Assembly

The scheme described in the last report has been further modified since it was found that the heavy slugs tended to pull the helix out of place during the assembly process. The last tube assembled had variations in pitch of  $\pm 4$  percent along its length.

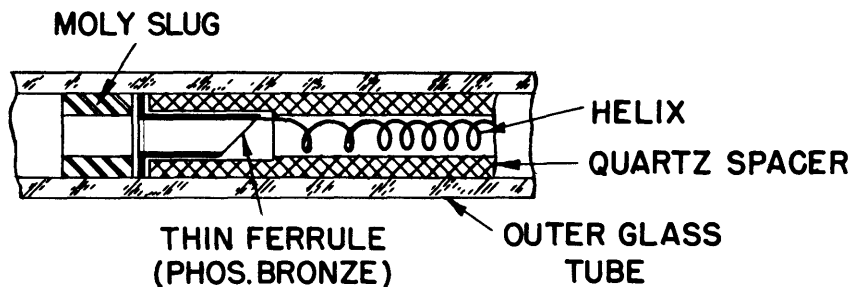


Fig. VIII-2 Detail of helix assembly for low voltage traveling-wave tube.

The thin ferrules, weighing only a fraction of an ounce, are welded to the helix and clamped between the quartz spacers. The heavy slugs are then dropped into the glass tube, one at either end of the helix, and the whole assembly clamped together by axial pressure.

#### 2. Gun Design

The tank design for a low current gun referred to in the last report has been tested, and the results are plotted in Figures VIII-3 and 4. The collector current is a much slower function of cathode temperature than is the anode current. Although no quantitative analysis has been carried out, it is believed that the effect of cathode temperature arises from the random velocity of emission of the electrons, as set forth in the last report.

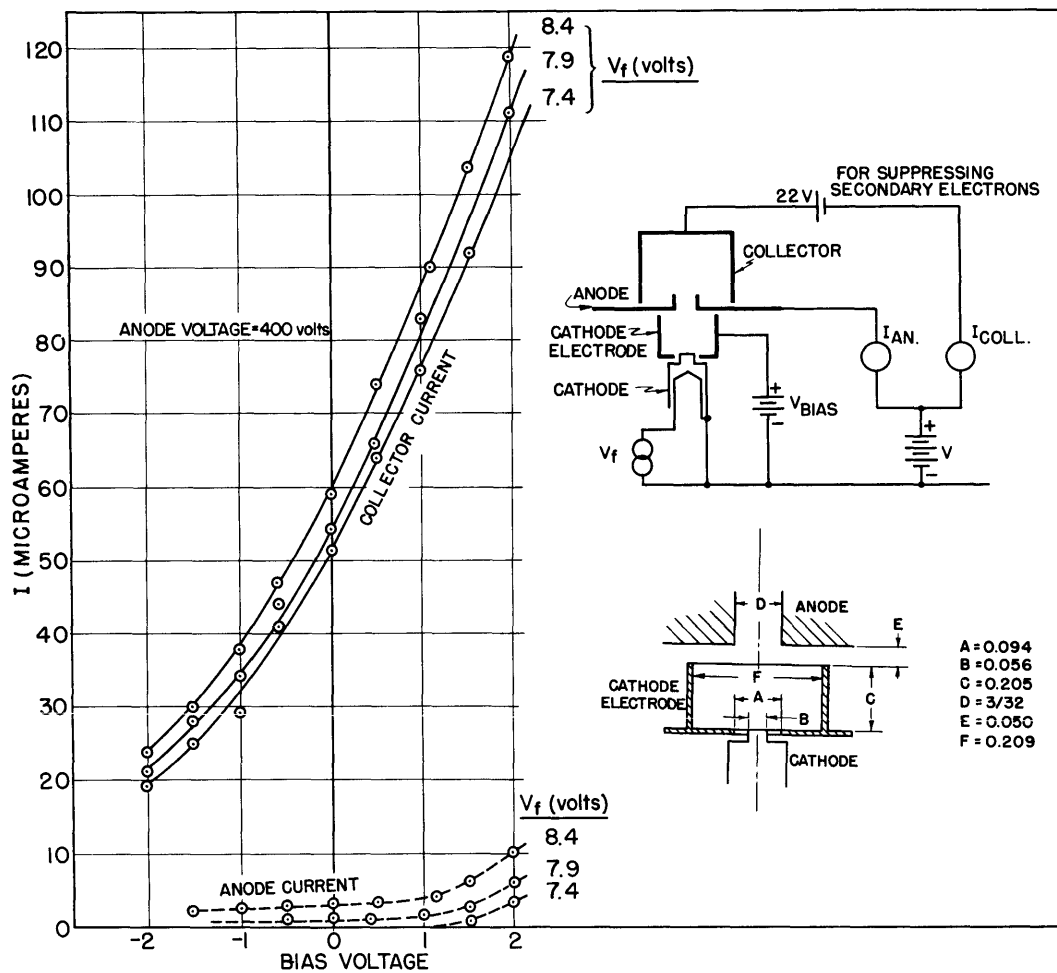


Fig. VIII-3 Low-current gun characteristics.

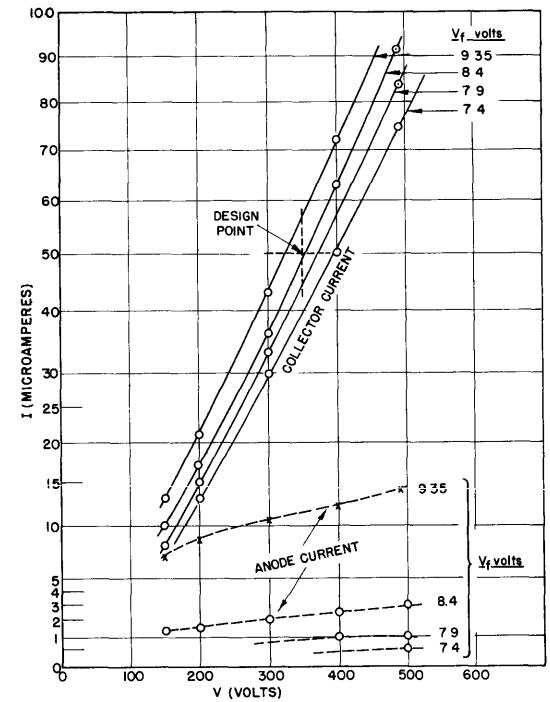


Fig. VIII-4 Low-current gun characteristic; effect of cathode bias.

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### E. DENSE ELECTRON BEAMS IN AXIAL MAGNETIC FIELDS

The following theoretical analysis has been carried out during the past quarter. The method of attack is based on the work of Dr. C. C. Wang of the Sperry Gyroscope Company.

The system of coordinates used is cylindrical  $(r, \theta, z)$ . Axial symmetry is assumed so that  $\theta$  becomes an ignorable coordinate. Uniform axial velocity ( $\dot{z}$ ) is assumed for all electrons, so that for any electron  $z$  is proportional to the time  $t$  and the problem is thus reduced to one in which the variables are  $t, r, \dot{r}, \dot{\theta}$ . The conservation of angular momentum is employed to solve for  $\dot{\theta}$  in terms of  $r, t$ , and the given magnetic field density  $B$ . It is found that at any instant the angular velocity  $\dot{\theta}$  depends on the difference in magnetic flux  $\Psi$  threading the circle of radius  $r$  about the  $z$  axis, and the flux  $\Psi_0$  threading a similar circle of radius  $r_0$  from which the electrons started at the cathode.

It is thus possible to eliminate  $\dot{\theta}$  from the equations and to derive the differential equation of motion for any electron in terms of  $r$  and  $t$ , the known parameters being the electrostatic potential  $\phi$  and the magnetic field distribution and the position of the cathode.

The electrostatic potential is calculated by assuming a certain charge density distribution  $\rho(r)$  independent of  $z$ . An expression for  $\phi(r)$  has been derived for the region of electron flow ( $r_a \leq r \leq r_b$ ) by expressing  $\rho(r)$  in this range in the form of a power series

$$\rho(r) = \sum_{n=-1}^{\infty} \rho_n r^n .$$

The electrostatic potential  $\phi(r)$  due to the beam itself and to the presence of the inner and outer cylindrical electrodes is then evaluated as a power series

$$\phi(r) = \sum_{n=0}^{\infty} \phi_n r^n ,$$

where the  $\phi_n$  are expressed in terms of the  $\rho_n$ .

Finally the differential equation of motion is derived. This is a second order, non-linear equation which can be integrated once to yield an energy equation. The energy equation may be thought of as defining a potential trough.

If the electron under consideration is specified by its equilibrium radius  $r_0$  and if we write  $r = r_0(1 + \delta)$  we can simplify the differential

equation to the form  $\ddot{\delta} = a_0 + a_1\dot{\delta} + a_2\delta^2 + \dots$ , where the  $a_n$  are expressed in terms of the  $\varphi_n$  and hence in terms of the  $\rho_n$ .

Since  $\delta = 0$  denotes the equilibrium position,  $a_0 = 0$ . For stability, the first non-zero coefficient must have an odd subscript and must be negative. If  $a_1 < 0$  we can use a linear approximation if  $\delta \ll 1$ . If  $a_1 = 0$  the solution is non-linear for any size  $\delta$ .

The analysis yields information as to the necessary field configuration, or alternatively, the necessary cathode position, by consideration of the quantity  $\Psi - \Psi_c$  mentioned previously.

One particular case has been treated rather extensively and design information has been obtained for it. This is the linear case where  $\varphi$  is of the form  $\varphi = \varphi_0 + \varphi_2 r^2$ . It applies to a uniform solid electron beam, as treated by C. C. Wang, or to a uniform hollow beam in which the correct potential variation is maintained by inner and outer electrodes.

A few of the stability conditions have been derived for the cases where only the first few  $a_n$  are present. These are all of the form,  $B > \text{some function of the } \rho_n$ .

Solution of the non-linear cases ( $a_1 = 0$  or  $\delta$  not  $\ll 1$ ) will have to be carried out numerically. None of these have been attempted yet, as there is not sufficient information about the actual magnetic field configuration or about the region between the cathode and the uniform beam section, i.e., the electron gun.

A brief analysis which must be further examined indicates that it is possible for the thermal velocities of emission to have considerable effect on the validity of the analysis in certain cases. The initial tangential component of velocity can cause appreciable error if the system is designed so that  $\Psi - \Psi_c$  is approximately zero. This condition occurs when we have a hollow beam with no inner electrode.

While a theoretical analysis of the gun region in which electrons are accelerated appears to be very complicated, it is possible that the rather simple energy conditions may provide a method of gun design. It should be possible to design an electron gun of the Pierce type which is modified to take account of the unavoidable magnetic field. Here the rotational energy will appear as correction terms to the usual Langmuir-Blodgett potential distribution for conical flow. This procedure also requires a detailed knowledge of the magnetic field in the gun region.

Although the experimental procedure is still not definite, a few of the pieces of necessary equipment have been started.

A demountable glass vessel for the electronic tests has been made by

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the glass shop. A non-magnetic support system upon which electrodes can be mounted and adjusted has been built to fit this vessel.

A long solenoid to fit around the glass vessel is in the process of construction. There is also a set of probe coils, mounted so as to measure  $\Psi$  directly, under construction. These should eliminate the need to measure B from point to point and to integrate in order to find  $\Psi$ .

A small air-driven probe coil for measuring magnetic field has been designed, built and tested, following the suggestions of Mr. G. C. Dewey of Federal Telecommunications Laboratory. A simple resistance-capacitance circuit renders the output of this coil essentially independent of speed.

L. A. Harris

### F. MICROWAVE NOISE STUDIES

A program has been initiated to investigate experimentally the noise in electron beams at microwave frequencies. Work in the last quarter has been devoted to constructing and checking measuring apparatus. The noise in the beam under study can excite a resonant cavity, and a sensitive super-heterodyne receiver can then measure the noise signal from the cavity by comparing it, through a calibrated microwave attenuator, with a standardized microwave noise source.

The following components, for use at S-band, have been completed:

#### 1. Microwave Noise Source

Such a unit has been described by W. W. Mumford of the Bell Telephone Laboratories. Our model consists of an F-5001 fluorescent lamp, 5 inches long and 9/16 inch in diameter located H-wise in an S-band waveguide fitted with a plunger and screw for impedance matching. A panel has been made with controls for starting the lamp and adjusting the d-c lamp current which affects the match. According to Mumford such a device has an effective temperature of 11,430°K.

#### 2. Receiver

A "cascode" pre-amplifier, amplifier, and detector for 30 Mc, built by G. E. Duvall (see R.L.E. Technical Report No. 82), have been set up and adjusted for use as the i-f stage of our receiver. These units have been carefully designed and are provided with a CV172 noise diode with which it has been verified that the noise figure of the amplifier (with 10,000 ohms input impedance and no input transformer) does not exceed 2. Necessary modifications to permit the input to be connected to a crystal mixer include

the addition of an input transformer for impedance matching, a crystal current meter and filter network, and suitable cable connections.

An S-band waveguide mixer has been chosen and matched at the desired frequency with the crystal current adjusted to provide optimum conversion efficiency and minimum noise. A TVN-7BL klystron signal generator is being used as a local oscillator.

The receiver has been tentatively assembled and a substantial reading on the detector output meter has been obtained upon connecting the standard noise source to the mixer input. A. Karp

#### G. ANALYSIS OF TRAVELING-WAVE TUBES

An algebraic solution of the characteristic equations of a traveling-wave tube has been carried out for the case of a lossy transmission line at synchronous beam velocity. (The report by J. H. Tellotson, "Explicit Forms of the Propagation Function of a Traveling-Wave Tube", Electronics Research Laboratory, Stanford University, came to the author's attention only a month ago.) If the forward waves are expressed by propagation constants  $\Gamma_n = j\beta_0 + \Delta_n$ , where the transmission line is characterized by  $\alpha_0 + j\beta_0$ , we get for the values of  $\Delta_n$

$$\Delta_1 = \frac{\alpha_0}{3} + A + B$$

$$\Delta_{2,3} = \frac{\alpha_0}{3} - \frac{A+B}{2} \pm j \frac{A-B}{2} \sqrt{3}$$

where

$$A = \sqrt[3]{\frac{\alpha_0^3}{27} + \frac{\beta_0^2 C^3}{2} (a\alpha_0 + j\beta_0)} + \sqrt{\left[ \frac{\beta_0^2 C^3 (a\alpha_0 + j\beta_0)}{2} \right]^2 + \frac{\alpha_0^3 \beta_0^2 C^3 (a\alpha_0 + j\beta_0)}{27}}$$

$$B = \sqrt[3]{\frac{\alpha_0^3}{27} + \frac{\beta_0^2 C^3}{2} (a\alpha_0 + j\beta_0)} - \sqrt{\left[ \frac{\beta_0^2 C^3 (a\alpha_0 + j\beta_0)}{2} \right]^2 + \frac{\alpha_0^3 \beta_0^2 C^3 (a\alpha_0 + j\beta_0)}{27}}$$

These are valid for about  $\alpha_0 < \beta_0/5$ , where  $a$  is a coupling constant between beam and helix.

For the usual traveling-wave tube, with an almost lossless helix,  $\alpha_0^3/\beta_0^3 C^3 \ll 1$ . Then

$$\Delta_1 \approx \frac{\alpha_0}{3} - j\beta_0 C$$

$$\Delta_{2,3} \approx \left( \frac{\alpha_0}{3} \pm \beta_0 C \frac{\sqrt{3}}{2} \right) + j \frac{\beta_0 C}{2} .$$



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If we have a very lossy section of helix as in the case of lumped loss, then  $\beta_o^3 C^3 / \alpha_o^3 \ll 1$ . This results in

$$\Delta_1 = \alpha_o$$

$$\Delta_{2,3} = \mp \sqrt{2} \beta_o C (1 - j) \quad .$$

Further work is being carried out on the problem of finding the best position of a lumped loss section of length  $l_1$ , along a helix of total length  $l_o$ .

L. D. Smullin

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